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ACCELERATION AND COLLISION OF ULTRA-HIGH ENERGY PARTICLES USING CRYSTAL CHANNELS

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ABSTRACT

We assume that, independent of any near-term discoveries, the continuing goal of experimental high-energy physics (HEP) will be to achieve ultra-high center-of-mass energies early in the next century. To progress to these energies in such a brief span of time will require a radical change in accelerator and collider technology. We review some of our recent theoretical work on high-gradient acceleration of charged particles along crystal channels and the possibility of colliding them in these same strong-focusing atomic channels. An improved understanding of energy and emittance limitations in natural crystal accelerators leads to the suggestion that specially manufactured nano-accelerators may someday enable us to accelerate particles beyond 10^{18} eV with emittances limited only by the uncertainty principle of quantum mechanics.

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INTRODUCTION

High-energy physics has progressed twelve orders of magnitude in energy during the last one-hundred years (1 eV to 10^{12} eV or 1 TeV). Modern high-energy colliders are both microscopes and time machines allowing us to probe fundamental physics at distances of 10^{-16} centimeters and hence understand the relevant phenomena 10^{-10} seconds after the Big Bang. It is thought by some that by advancing only one or two orders of magnitude higher in energy, experiments will place enough constraints on unified field theories to yield one consistent "Theory of Everything" including gravity. Machine builders instead assume that regardless of any intermediate discoveries, the continuing goal of experimental high-energy physics will be to achieve ultra-high center-of-mass energies in the next century. To reach these energies with their attendant high luminosity in such a brief span of time will require a radical change in accelerator and collider technology. In all likelihood more than one paradigm shift in accelerators will be needed. In this paper we review some of our recent work [1] on a concept that may enable high-energy physics to reach energies of order 10^{18} eV early in the next century.

Ten years ago the present authors made a cursory study of a concept to accelerate positively-charged particles along crystal channels by the electron plasma waves in metals [2,3]. The maximum electric field of a plasma wave is of order $\sqrt{n_o}$ V/cm, where n_o is the electron number density in units of cm^{-3}. Acceleration gradients of 100 GV/cm or more were implied based on the electron densities in solids. The strong electrostatic focusing of the atomic channels combined with the high gradients were found to maintain low beam emittance in spite of multiple scattering on channel electrons. The technological demands to excite such large amplitude plasma waves with lasers or particle beams appeared daunting then, and crystal behavior at picosecond to femtosecond time scales and high power densities was uncertain at best.

The development of ultra-short pulse-length lasers, nano-fabrication technology and a better experimental and theoretical understanding of high energy density effects in solids motivated us to return to the topic of a crystal channel accelerator. An improved picture of a crystal accelerator has emerged which allows us to further illucidate the advantages of crystals for acceleration and emittance control as well as point out the constraints imposed by the use of natural crystals as high-energy particle accelerators. Limits on high luminosity may ultimately be more difficult to overcome than achieving ultra-high energy. The quantum mechanical control of colliding particle trajectories to the level of the uncertainty principle may be required to achieve high luminosity.

CRYSTAL ACCELERATION AND EMITTANCE DAMPING

The basic concept of crystal channel acceleration combines plasma wave acceleration [4] with the well known channeling phenomenon [5] to allow positively charged particles to be accelerated over long distances without colliding with nuclei in the accelerating medium. Positively charged particles are guided by the average electric fields produced by the atomic rows or planes in a crystal. The particles make a series of glancing collisions with many atoms and execute classical oscillatory motion along the interatomic channels. In contrast negatively charged particles oscillate about the atomic nuclei and rapidly suffer large-angle Coulomb scattering.

Acceleration in the crystal is provided by an electron plasma oscillation [6] with phase velocity near the speed of light. The maximum electric field is roughly $\mathcal{E}_0 = m_e\omega_p c/e$, where m_e is the electron rest mass and $\omega_p = (4\pi n_o e^2/m_e)^{1/2}$ is the electron plasma frequency. In convenient units, $\mathcal{E}_0(V/cm) \simeq 0.96(n_o(cm^{-3}))^{1/2}$. Doped semiconductors typically have carrier densities of 10^{14} to 10^{18} cm^{-3} corresponding to $\mathcal{E}_0 = 10$ MV/cm to 1 GV/cm, the same as typical laboratory gas plasmas. Conduction electrons in metals have densities of 10^{22} to 10^{23} cm^{-3} while the total electron density of solids is of order 10^{24} cm^{-3} implying gradients of order 1 TV/cm.

A basic obstacle to accelerating particles over long distances in crystals is beam loss from dechanneling. The transverse momentum of channeled particles increases due to collisions with electrons in the interatomic channels. Dechanneling occurs when a particle's transverse kinetic energy $E\psi^2/2$, where $E = \gamma mc^2$ is the total particle energy, allows it to overcome the channel's potential energy barrier V_c ($\sim 10 - 1000\, ze$ volts for a particle of charge ze). At this point close encounters with atomic cores quickly scatter particles out of the channel. This defines the critical channeling angle $\psi_c = (2V_c/E)^{1/2}$. In many crystals the electron density n over most of the channel is roughly constant. From Poisson's equation the channel potential energy function in either plane is simply $V = K_c x^2/2$, where $K_c = 4\pi z e^2 n$ is the focusing strength. The channel half-width a corresponds to the point where $V = V_c = K_c a^2/2$.

In the harmonic potential approximation, each crystal channel acts like a smooth focusing accelerator with betatron focusing function (wavelength/2π of transverse oscillations) $\beta_F = (E/K_c)^{1/2} = a/\psi_c$. The normalized *rms* channel acceptance, $A_n \equiv \gamma a^2/2\beta_F = \gamma a\psi_c/2$, defines the available transverse phase space for a channeled particle. Multiple scattering in a transverse focusing system randomly excites betatron oscillations leading to growth in the normalized *rms* emittance $\varepsilon_n = \gamma\varepsilon = \gamma\sigma^2/\beta_F$, where ε is the geometric emittance, and σ^2 is the *rms* amplitude of the particle [7]. In this terminology, dechanneling occurs when the particle emittance exceeds the channel acceptance. The emittance growth is $d\varepsilon_n/ds = (\gamma\beta_F/2)d\langle\psi^2\rangle_{ms}/ds$, where the increase in *rms* angular divergence is $d\langle\psi^2\rangle_{ms}/ds = \psi_c^2/2\ell_d$. The characteristic dechanneling

length is $\ell_d = \Lambda E/ze$, and Λ is the dechanneling constant ($\sim a^2$). In natural crystals where $a \simeq 1$ to 3 Å, Λ is typically of order 1 to 10 μm/MV.

Particle dechanneling in a crystal accelerator is modified by several effects. Acceleration reduces multiple scattering with increasing energy. The presence of any transverse fields in addition to the natural channel forces will change the betatron focusing function and channel acceptance by modifying the focusing strength K_c into a total strength K. Charged particles oscillating in a transverse focusing system radiate and make transitions to lower energy levels of the potential with an energy-independent decay constant $\Gamma_c = 2r_{cl}K/3mc$, where $r_{cl} = (ze)^2/mc^2$ is the classical particle radius [8,9]. These radiative transitions act to damp the particle's normalized emittance. Collisional energy loss to electrons in the channel can also damp emittance (ionization cooling) but with an energy-dependent decay parameter $E^{-1}(dE_{coll}/ds) = (E/m_ec^2)d\langle\psi^2\rangle_{ms}/ds$ for a relativistic particle.

Combining these effects, the evolution equation for the normalized emittance in a crystal channel accelerator is [1]

$$\frac{d\varepsilon_n}{ds} = -\frac{\Gamma_c}{c}(\varepsilon_n - \hbar/2mc) - \frac{zeK_ca^2}{2m_ec^2\Lambda E}\varepsilon_n + \frac{zeK_ca^2}{4mc^2\Lambda(KE)^{1/2}}\,, \qquad (1)$$

where $E = E_i + zeGs$, E_i is the initial particle energy, and G is the (net) acceleration gradient which is assumed to be a constant. The term $\hbar/2mc$ is the minimum quantum emittance of a particle in the ground state of the transverse potential. Because of the different energy dependencies in the three terms of Eqn. (1), not all terms are equally important in an arbitrary energy regime. The effectivenes of ionization cooling clearly falls off rapidly with increasing energy. In the limit of high gradients ($G \gg K_ca^2/\Lambda m_ec^2 \sim 1$ MV/cm) and short channel lengths ($\Gamma_cs/c \ll 1$), ionization cooling and radiative damping have a negligible effect on the emittance evolution in the channel compared to acceleration, and the emittance becomes

$$\varepsilon_n = \varepsilon_{ni} + \frac{(K_c/K)A_n}{\Lambda G}(1 - (\gamma_i/\gamma)^{1/2})\,. \qquad (2)$$

Accelerated particles remain indefinitely channeled provided $G \geq K_c/K\Lambda$. This corresponds to 1 to 10 GV/cm in natural crystal channels when $K = K_c$. Note that the equilibrium *rms* amplitude is $\sigma^2 = (K_c/K)a^2/2\Lambda G$.

For distances $s \gg c/\Gamma_c$ where radiative damping is important and $E \gg E_i$, the normalized emittance can be written approximately as

$$\varepsilon_n(s) = \frac{\hbar}{2mc} + \frac{3mc^2(K_c/K)a^2}{8ze\Lambda(zeGKs)^{1/2}}\,, \qquad (3)$$

which damps like $\gamma^{-1/2}$ provided the net gradient G can be maintained constant with the increasing radiative energy loss. Note that the *rms* amplitude σ^2 of

the channeled particle damps like γ^{-1} in this regime. The presence of K_c in Eqn. (3) reflects the deleterious effect of electron multiple scattering, and prevents one from realizing the ideal quantum emittance in such a collective accelerator.

To obtain small emittances and high luminosity in a channeling accelerator then, it is advantageous to have a high acceleration gradient and strong transverse focusing such that $K \gg K_c$. In practice the available technology will limit the plasma wave amplitude G_0 that can be generated in a crystal channel accelerator. When the magnitude of the radiative energy loss rate $(dE/ds)_{rad} = -\Gamma_c \gamma^2 K \sigma^2$ becomes comparable to zeG_0, a limiting energy is reached. In the regime $\Gamma_c s/c < 1$ where Eqn. (2) is valid, the radiation rate is proportional to γ^2, and the limit is

$$E_{max} \simeq \sqrt{\frac{3\Lambda}{zea^2 K K_c}} m^2 c^4 G_0 \, . \tag{4}$$

The presence of K and K_c in Eqn. (4) reflects the competing effects of strong focusing and multiple scattering in the channel. This places a fundamental energy limit on natural crystal accelerators with $K = K_c$ because the electron density ($\sim K_c$) is fixed by the atomic structure. For example if $G_0 = 100$ GV/cm and $K = K_c = 20$ eV/Å^2, then the maximum energy is about 300 GeV for positrons, 10^4 TeV for muons and 10^6 TeV for protons. On the other hand if one can artificially arrange that $K_c < (4ze\Lambda/3a^2)K$, accelerated particles will enter the regime $s > c/\Gamma_c$ before the limit (4) is reached. Here the radiation rate is only proportional to γ, and the energy limit is $E_{max} \simeq 4m^2c^4\Lambda G_0/K_c a^2$.

CRYSTAL BEHAVIOR AT HIGH GRADIENTS

Only for acceleration gradients $G \geq \Lambda^{-1} \simeq 1 - 10$ GV/cm will particles remain channeled over long distances in a natural crystal accelerator. Since Λ is proportional to a^2, it may be useful to consider artificially wide channels ($a > 3$ Å) to reduce the gradient demand, at least for early experiments where gradients may be limited. Still, a large amplitude plasma wave with a field of 100 GV/cm or more is ultimately desirable to shorten the accelerator and keep the emittance as low as possible.

Two regimes of the crystal accelerator can be distinguished based on whether the plasma wave amplitude or the fields used to excite the wave are greater than or less than $I/r_a \simeq 1 - 10$ V/Å, where I is the ionization energy of electrons in an atom of size r_a. For fields greater than this, the Coulomb potential of an atom is sufficiently deformed to induce significant tunneling ionization. For an oscillating electric field $\mathcal{E}$, electrons tunnel from atoms within a time $v_e/c\epsilon\omega$, where $v_e = (2I/m_e)^{1/2}$, $\epsilon = e\mathcal{E}/m_e\omega c$ is the normalized field strength, and ω is the frequency [10]. Typically v_e/c is of order the fine-structure constant $\alpha \simeq 1/137$, so for field strengths $\epsilon > 10^{-2}$, electrons escape

the atom within an oscillation period. In this high field regime, the lattice ionizes, but does not yet dissociate, on this time scale. If an intense laser ($> 10^{14} - 10^{15}$ W/cm^2) is used to build up the plasma wave, the lattice will already be in this ionized state prior to plasma-wave formation.

For laser and plasma fields below 0.1 to 1 GV/cm, reusable crystal accelerators can probably be built which might survive multiple pulses. Plasma wave decay is determined by interband transitions with a timescale of 10 to 100 $\omega_p{}^{-1}$ in this regime [11]. For fields above a GV/cm, only disposable accelerators, perhaps in the form of fibers or films, are possible. The lattice is highly ionized by the laser driver used to excite the plasma wave in a few optical periods, and the free electron density immediately increases to 10^{23} cm^{-3} or more for any solid. Plasma wave build-up and channeled particle acceleration must occur before the ionized lattice disrupts due to ion motion. The lattice dissociates by absorbing plasmon energy on a timescale determined by the inverse ion plasma frequency $\omega_{pi}^{-1} = (m_i/m_e)^{1/2}\omega_p^{-1} \sim 10^{-14}$ sec, where m_i is the ion rest mass. Within this time, the ions have not moved appreciably, and the lattice remains sufficiently regular to allow channeling.

The generation of large-amplitude plasma waves in a crystal requires an intense power source to supply the plasma-wave energy before the lattice dissociates. A gradient of 100 GV/cm corresponds to an energy density of 3×10^7 J/cm^3, and this must be created and used within ω_{pi}^{-1}. Conceivably side-injected laser [12], laser wakefield [13] or another mechanism could be used to excite plasma waves in a crystal channel collider. For low gradients ($<$ 1 GV/cm) reusable accelerators probably would take the form of crystal slabs on some alignable substrate. For higher gradients replaceable films or fibers are more appropriate since these are expected to be vaporized on each pulse. Alignment is certainly problematic here, and awaits the invention of fast, repeatable atomic-scale positioning. This is needed to permit staging of crystal accelerator sections with atomic precision and maintain a straight accelerator. Dislocations, unintended crystal curvature, and misalignment between sections will likely be the practical limits to long crystal accelerators.

THE CRYSTAL CHANNEL COLLIDER

The emittance solutions above suggest that small beamlets can be maintained with a high acceleration gradient and strong transverse focusing in crystal channels. As noted in Ref. 9, the small beamlets can in principle be brought into collision with a high probability if the crystals of each collider arm can be aligned channel to channel. This improves the luminosity, but limitations are still reached because the bunch population cannot be made arbitrarily high, as is true in all accelerators with small transverse dimensions and short wavelengths. The crystal lattice disrupts after about 10^{-14} sec, or a hundred plasma oscillations, so the number of accelerated bunches in each

channel is limited to $n_b \simeq 100$. The number of particles in each bunch is denoted by N. The bunches pass through all bunches of the oncoming train so the luminosity is proportional to $n_b^2 N^2$. Of course the accelerating crystal contains a huge number of parallel atomic channels, n_{ch}, each accelerating its own n_b bunches. The luminosity of this parallel array of accelerators is then $L = f_{rep} n_{ch} n_b^2 N^2 \gamma / 4\pi\beta^* \varepsilon_n$. Here f_{rep} is the repetition rate of the accelerator, and β^* is the channel beta function $(E/K)^{1/2}$ since no additional focusing at the crossing is assumed.

For the sake of discussion, let us assume a natural crystal with $K = K_c$, $a \simeq 1$ Å , and that the emittance is given by Eqn. (2) with an acceleration gradient $G = 10\Lambda^{-1} \simeq 100$ GV/cm. The number of accelerated particles in each plasma oscillation bucket is limited by beam loading [14] to a value $n_{ch} N \simeq n_{ch} A_{ch} G / 8\pi e$, where $A_{ch} \simeq \pi$ Å^2 is the area of an atomic channel. This yields $N \simeq 10$, and the luminosity becomes $L(cm^{-2} sec^{-1}) \simeq 2 \times 10^{22} f_{rep} n_{ch}$. To use a proton collider for discovering new physics at a center-of-mass energy E_{cm} may require a luminosity $L(cm^{-2} sec^{-1}) \simeq 10^{29} (E_{cm}(TeV))^2$, although this may be an overestimate. This implies $f_{rep} n_{ch} \simeq 5 \times 10^{12}$ at 10^3 TeV and 5×10^{18} at 10^6 TeV. The average beam powers at these energies are 800 GW and 8×10^8 TW, respectively. These high powers result from the inherent disadvantage of having many parallel accelerators each with a small number of particles per bunch.

The situation can be improved according to Eqn. (3) by having low electron density and/or strong focusing ($K \gg K_c$) in each channel so that particles would enter the radiation damping regime where σ^2 damps like γ^{-1}, thus increasing the luminosity. The method for doing this for each channel independently is unclear, though we offer some speculation here. The desire to reach emittances limited by the uncertainty principle seems to imply the need for individually manufactured nano-accelerators bundled in a parallel array and each containing strong transverse focusing elements. The radius of each nano-accelerator tube would be much less than a plasma wavelength so a uniform electron plasma oscillation would exist in the bulk but larger than 10 Å so that the electron density near each channel center would be extremely low (to eliminate multiple scattering). Radiative damping would reduce the beam emittance in each tube to $\hbar/2mc$. This may have interesting consequences which we have only begun to explore. Such a cooled beam might exhibit a condensate behavior in which channeled particles form pairs leading to an ordered state relatively impervious to multiple scattering. In analogy to a superconducting transition this would appear to require some residual attractive force between channeled particles so that a lower energy condensed state would exist. Whether the nanotube array can exhibit a phonon spectrum suitable to produce such a residual interaction, as occurs in familiar superconductor lattices, is under study.

CONCLUSION

The concept of a crystal channel collider provides a useful arena in which to explore new ideas for particle acceleration. The chief advantages of collective acceleration in crystal channels remain the avoidance of emittance growth due to multiple scattering on atomic nuclei and the potential for very high acceleration gradients. The crystal naturally provides a confined, uniform electron plasma for acceleration and a strong focusing system to maintain a small beam size and increase luminosity. In natural crystal accelerators, multiple scattering on channel electrons competes strongly with radiative emittance damping, and keeps the transverse particle amplitudes from being reduced to the quantum mechanical limit. The resulting radiative energy loss limits the maximum attainable energy which is then proportional to the acceleration gradient that can be generated. For a gradient of 100 GV/cm, proton energies of order 10^{18} eV are possible. Channels with low electron density and/or strong additional focusing are suggested to raise the energy limit. Artificial nanotube accelerator arrays offer the possibility of cooling emittances to values determined by the uncertainty principle but still providing collective acceleration with electron plasma waves. Work in progress involves exploring whether these cooled beams might exhibit a condensate behavior which, like Cooper pairs in a superconductor, are much more impervious to scattering than single particles. This would open the way to enhancing luminosity by manipulating the wavefunctions of ultra-high energy channeled beams.

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